HIP-2004-08/TH

Dumping inflaton energy density out of this world

Kari Enqvist [1], Anupam Mazumdar [2], and A. Pérez-Lorenzana [3]

[1] *Department of Physical Sciences, University of Helsinki,*
and Helsinki Institute of Physics, P.O. Box 9,
FIN-00014 University of Helsinki, Finland

[2] *CHEP, McGill University, 3600 University Road,*
Montréal, Québec, H3A 2T8, Canada

[3] *Departamento de Física, Centro de Investigación y de Estudios Avanzados del I.P.N.*
Apdo. Post. 14-740, 07000, México, D.F., México

Abstract

We argue that a brane world with a warped, infinite extra dimension allows for the inflaton to decay into the bulk so that after inflation, the effective dark energy disappears from our brane. This is achieved by the redshifting of the decay products into infinity of the 5th dimension. As a consequence, all matter and CMB density perturbations could have their origin in the decay of a MSSM flat direction rather than the inflaton. We also discuss a string theoretical model where reheating after inflation may not affect the observable brane.

I. INTRODUCTION

Recent observations [1] strongly support a period of primordial inflation. Besides making the universe flat and homogeneous, inflation is the only known dynamical mechanism which can stretch small quantum fluctuations outside the Hubble horizon. These perturbations act as seeds for the large scale structures in the Universe. However, despite of the success of the inflationary paradigm (for a review, see [2]), we know very little about the inflationary sector. The inflaton potential must nevertheless be very flat with a very small self coupling; likewise, its coupling to other fields must be extremely weak. Such small couplings are hard to come by without fine tuning, which renders inflaton to a gauge singlet whose couplings can be adjusted at our will. Given this, the immediate question is, what is the inflaton decaying into?

Eventually the cold inflationary Universe must reheat with the Standard Model (SM) degrees of freedom, or, as the current theoretical prejudice dictates, with the Minimally Supersymmetric Standard Model (MSSM) degrees of freedom. MSSM contains a number of flat directions along which the renormalizable part of the potential vanishes (for a review, see [3]). During inflation the massless fields corresponding to the flat directions receive scale-invariant perturbations. It would be tempting to associate them with reheating and the generation of CMB perturbations [4, 5, 6, 7]. This would require that the flat directions will eventually dominate over the radiation produced by the inflaton decay. In other words, the flat direction would have to act as an MSSM curvaton [8, 9, 10]. However, it turns out that such domination is not possible unless the inflaton decays into some hidden degrees of freedom, rather than into MSSM radiation [4, 5].

In this respect brane world scenarios, where the Universe is regarded as a three dimensional hypersurface embedded in a higher dimensional bulk, bring along new, interesting possibilities. The SM degrees of freedom are assumed to be stuck on a brane while gravity is propagating in the entire bulk. The bulk could also have a non-trivial background geometry which allows for the zero mode of graviton to be trapped at the brane location, such as in the case of an anti de-Sitter (adS) bulk in the Randall-Sundrum type models [11, 12]. The value of the Newton's constant requires the fundamental scale to be fairly large, 10^{18} GeV $\geq M_s \geq 10^3$ GeV. In these models the inflaton, again treated as a gauge singlet, could either live on the brane or in the entire bulk. There is also the exciting pos-

sibility that the inflaton energy density does not reheat the Universe, but gets deposited in the infinite bulk or onto the adS horizon. In this respect the inflaton potential could be treated as a kind of dark energy for the MSSM brane. It has been shown [6] that if the dark energy of the inflaton field can be transferred into the bulk so that it no longer is visible on our brane, even the simplest MSSM flat directions can act as curvatons and provide both all the matter and the density perturbations in the Universe.

The brane world scenarios are supported by the string theory, where there is a natural explanation for the construction of MSSM like brane with a help of coincident stack of Dp branes (p is the number of spatial dimensions along the brane, p is odd (even) in type IIA (IIB) string theories) attached to some orbifold point [13] [1]. The open strings attached to Dp branes act as sources for gauge fields and gravity again propagates in the entire bulk. In this kind of framework the inflaton may be regarded as a moduli, for example the physical separation between a Dp and anti-brane $\bar{D}p$ brane, or the angular separation between $Dp - Dp$ or $Dp - \bar{D}p$ branes (for a review see [15]). Inflation may end by virtue of tachyon condensation when branes approach close to the string scale [16], or with a help of many tachyons as in the case of assisted inflation [17]. It is however not guaranteed that inflaton will reheat the Universe with the MS(SM) degrees of freedom. One could rather argue that it is more likely that the inflaton will reheat the bulk.

The purpose of this paper is to construct a brane world model with a warped bulk so that it is possible to localize the inflaton energy density away from the MS(SM) like branes. We will argue that the inflaton energy can be redshifted away so that after inflation there is effectively no energy density other than that of the excited MSSM flat directions on our brane. For our purposes, the inflaton potential is a form of dark energy which is only responsible for making the Universe, parallel to the brane directions, large, homogeneous and isotropic.

The paper is organized as follows. In Section II we recapitulate some known results of the brane world models and discuss infinite extra dimensions. In Section III we present a brane-world where the dark energy can be dumped into the bulk instead onto the brane and estimate the escape rate of the inflaton decay products from the brane. In Sect. IV we motivate the model by considerations relating to string theoretical inflation. In Sect. V we

[1] For different constructions, see [14].

give our conclusions and discuss how the present results can be combined with curvaton-like scenarios involving MSSM flat directions to yield all matter and an adiabatic, scale-invariant spectrum of perturbations.

II. INFINITE EXTRA DIMENSION AND KK DECOMPOSITION

In this section we briefly recapitulate some of the already known results of the brane world models. We start with the simplest scenario assuming that there is a three dimensional hypersurface, called the brane, which carries MSSM degrees of freedom. The MSSM brane is embedded in a 5 dimensional space (the bulk) with a non-factorizable metric [11, 12] (for a nice review, see [18])

$$ds^2 = a^2(z)\eta_{\mu\nu}dx^\mu dx^\nu - dz^2\,, \tag{2.1}$$

where $\eta_{\mu\nu}$ is the four dimensional Minkowski metric. We take the extra dimension to be infinite. The brane is located at $z = 0$. The total action for gravity is given by

$$S_g = -\frac{1}{16\pi G_5}\int d^4x dz\sqrt{g^{(5)}}R^{(5)} - \Lambda\int d^4x dz\sqrt{g^{(5)}} - \sigma\int d^4x\sqrt{g^{(4)}}\,. \tag{2.2}$$

where Λ is a bulk negative cosmological constant which is related to the brane tension σ by the fine tuning relationship

$$\Lambda = -\frac{4\pi}{3}G_5\sigma^2\,. \tag{2.3}$$

The warp factor present in the metric has the form $a(z) = e^{-k|z|}$, with

$$k = \frac{4\pi}{3}G_5\sigma\,. \tag{2.4}$$

Here G_5 stands for the true gravitational coupling constant of the five dimensional theory, which defines the fundamental gravity scale as $M_* = (8\pi G_5)^{-1/3}$. The effective four dimensional Newton's constant $M_P = (8\pi G_4)^{-1/2} = 2.4\times 10^{18}$ GeV is given by

$$G_4 = k\ G_5\,. \tag{2.5}$$

This setup is inspired by adS/CFT correspondence [19], where the entire bulk has adS geometry. It has an interesting feature along the z axis in that the fifth dimension has a horizon at $z = \infty$. A particle that escapes from the brane and moves along a geodesic travels from $z = 0$ to $z = \infty$ in a finite proper time $\tau = \pi/2k$. In other words, $z = \infty$ is a particle horizon.

Another interesting property is that the spectrum of the KK gravitons has a localized massless mode around the brane, identified as the four dimensional graviton, plus a continuum of modes with wave functions which are oscillatory at large z,

$$h_m(z) = \text{const } \times \sin\left(\frac{m}{k}e^{kz} + \phi_m\right) , \tag{2.6}$$

while near the brane location, at $z = 0$, the wave function is suppressed:

$$h_m(z=0) = \text{const } \times \sqrt{\frac{m}{k}} . \tag{2.7}$$

By summing over all the KK modes, including the zero mode of the graviton, one finds a modification of the gravitational interaction between two point particles located on the brane. If their masses are m_1 and m_2 and the particle separation is r, the potential has the form

$$V(r) = -\frac{G_{(4)}m_1m_2}{r}\left(1 + \frac{\text{const}}{k^2r^2}\right) . \tag{2.8}$$

For distances $r \gg 1/k$ the correction to the Newtonian gravity is negligible small. Current experiments have tested the validity of Newton's law down to sub-millimeter distances, which implies that $k > 10^{-3}$ eV [20]. In this paper we will mostly assume that k and M_*, are close to the four dimensional Planck scale.

It is clear that with an infinite fifth dimension the KK modes of other bulk fields also possess a continuum of modes [21], and may also have a quasi-localized mode [22]. Consider for instance the case of a scalar bulk field on the background metric Eq. (2.1). The action is then given by

$$S_\chi = \int d^4x\, dz\, \sqrt{g^{(5)}}\left(\frac{1}{2}g^{ab}\partial_a\chi\partial_b\chi - \frac{1}{2}\mu^2\chi^2\right) . \tag{2.9}$$

The corresponding KK wave function is then defined as a solution to the field equation

$$\left[-\partial_z^2 + 4k\, sgn(z)\partial_z + \mu^2 - m^2/a^2(z)\right]\chi(z;m) = 0 , \tag{2.10}$$

where $m^2 = p^\mu p_\mu$ defines both the four dimensional mass and the KK level. Eq. (2.10) is supplemented by the boundary condition on the brane $\partial_z\chi(z = 0; m) = 0$, and the normalization condition $\int dz\, a^2(z)\chi(z;m)\chi(z;m') = k\delta(m - m')$. The general solution to Eq. (2.10) is given in terms of Bessel functions of index $\nu = \sqrt{4 + \mu^2/k^2}$, and can be written as [21, 22]

$$\chi(z;m) = \frac{1}{N(m)a^2(z)}\left[J_\nu\left(\frac{m}{ka(z)}\right) + A(m)Y_\nu\left(\frac{m}{ka(z)}\right)\right] , \tag{2.11}$$

where the normalization factor, N, and the coefficient A are functions of the continuous KK index m. One finds that [21, 22] $N(m) = \sqrt{1 + A^2(m)}/\sqrt{m/2}$ with

$$A(m) = -\frac{2\, J_\nu(m/k) + (m/k)J'_\nu(m/k)}{2\, Y_\nu(m/k) + (m/k)Y'_\nu(m/k)}. \tag{2.12}$$

For $\mu, m \ll k$ one can approximate the last expression by taking $\nu = 2$ and show that

$$A(m) \approx \frac{\pi}{4}\left(\frac{m}{k}\right)^2 \ . \tag{2.13}$$

Thus, the KK wave function evaluated at the brane is just

$$\chi(0, m) \approx \sqrt{\frac{m}{2}}\ . \tag{2.14}$$

Note that the functional behavior of the above expression is the same as for the graviton case in Eq. (2.7).

As noted in Ref. [22], this system has in general a resonance around the brane, i.e., there is a quasi-localized mode of non-zero mass; that is, there is no truly bound state in the spectrum. This can be visualized in a simple way: the continuum of modes is determined by the asymptotic form of the field equation at large z, where the mass term μ^2 is negligible compared with $m^2/a^2(z)$, which shows that the spectrum does start at $m = 0$, independently of μ, but there are no bound states within the continuum. By exploring the KK modes one can show that there is a mode that actually has a complex eigenvalue $m = m_0 + i\Gamma$ [22]. Thus, this mode can be considered as a quasi-localized metastable state for which Γ gives the escape rate from the brane into the extra dimension towards infinity. For $\mu \ll k$ one finds $m_0 = \mu/\sqrt{2}$ and

$$\Gamma = \frac{\pi}{16}\left(\frac{m_0}{k}\right)^2 m_0\ . \tag{2.15}$$

In the following section we will use some of these results when considering the decay life time of the inflaton.

III. INFLATON DECAY INTO THE BULK IN A WARPED BRANE WORLD SCENARIO

Let us now discuss how after inflation the inflaton may disappear from the brane and leave behind an (almost) empty brane, with a minor impact on the later cosmological evolution. This is a radical point of view that, however, can easily be accommodated within the context

of infinite extra dimension models [23]. To be more specific, let us assume that the inflaton is a true 4D brane field, with a homogeneous distribution that dominates the energy density at the early Universe on the observable brane and gives rise to a period of inflation. Then the Friedmann equation has a quadratic dependence on the brane density ρ [24] so that

$$H^2 = \frac{1}{3M_P}\rho\left(1+\frac{\rho}{2\sigma}\right) , \tag{3.1}$$

which becomes the standard relation $H = \sqrt{\rho/3M_P}$ only for densities small compared to the brane tension [24, 25].

Once inflation comes to an end, the inflaton will decay, but instead of reheating the brane degrees of freedom, we now assume that it couples to the bulk fields alone, and decays into bulk degrees of freedom. This may happen, for instance, if the inflaton and the bulk fields carry some global quantum number while the brane degrees of freedom do not. All the inflaton energy would be radiated into the empty bulk after the end of inflation in the form of KK modes. These bulk modes carry momentum along the fifth dimension, so that they would simply fly away into the empty bulk, towards infinity, taking the inflaton energy away from the brane. The energy density of the inflaton will be gradually redshifted into the bulk before becoming vanishingly small. A small fraction, however, may act as a dark energy on the brane. We will comment on this below.

It is interesting that whether the inflaton density is larger than brane tension or not becomes irrelevant for the purposes of the present discussion. Inflation could well take place in the non standard regime of the theory, without leaving any visible trace on the subsequent thermal evolution of the Universe [26].

Our scenario can be thought of as a hot radiating plate cooling down by emitting its energy into the cold surrounding space. It is not hard to see that such cooling process is extremely efficient. To demonstrate the feasibility of the idea, let us consider the coupling of the inflaton to a bulk scalar field φ, which in the complete 5D theory can be written as

$$\sqrt{g(z)}\, h\, \phi(x)\, \varphi(x,z)\, \varphi(x,z)\, \delta(z)\, , \tag{3.2}$$

with h is corresponding coupling constant. After introducing the KK decomposition of the bulk field and integrating out the extra dimension one gets the effective coupling of the inflaton to the KK modes as

$$h\left[\chi(0,m)\chi(0,m')\right]\, \phi(x)\, \varphi_m(x)\, \varphi_{m'}(x)\, ; \tag{3.3}$$

where $\chi(0,m)$ are the z dependent wave functions of a KK modes of mass m, given in Eq. (2.11), evaluated at the brane position. The KK mass dependence of the effective couplings indicate that the inflaton would preferably decay into the heavy modes, i.e. those with the largest momentum along the fifth dimension. This scenario is similar to the one discussed in Ref. [27] for the cooling down of a hot brane by graviton emission, although there the KK gravitons were assumed to be thermally produced.

If the inflaton decays into the continuum of KK modes with masses smaller than m_ϕ, it is straightforward to estimate the total decay rate as

$$\Gamma_\phi = \int_0^{m_\phi} \int_0^{\sqrt{m_\phi^2 - m^2}} \frac{dm}{k}\frac{dm'}{k}\, h^2\, \frac{[\chi(0,m)\chi(0,m')]^2}{m_\phi} \approx \frac{h^2}{32}\left(\frac{m_\phi}{k}\right)^2 m_\phi\,; \tag{3.4}$$

where the RHS has been estimated in the limit where $\mu, m_\phi \ll k$ using Eq. (2.14). Since the inflaton is heavy, say, about the GUT scale, whereas k is close to M_P, the suppression on the decay rate is not large. As a consequence the inflaton may release all its energy into the bulk fields very efficiently.

Let us now discuss what happens to the energy that has been injected into the bulk. As already mentioned above, since KK modes have a fifth momentum, they will travel away from the brane, moving towards infinity. As the original energy density of the inflaton field is shifted away from the brane into the extra dimension, only the tail of the density distribution would be felt by the brane. It has been pointed out, however, that the energy emitted from the brane would eventually collapse to a black hole at the end of the space [28]. The presence of the black hole changes the brane expansion by introducing a new contribution to the Friedmann equation Eq. (3.1) which behaves as $2M_{BH}/a^4$, where a is the brane scale factor and M_{BH} is a parameter interpreted as the 5D "mass" of the black hole [29]. This term acts as a dark energy, which, provided that M_{BH} is small, has a subleading role in the early Universe. In addition, due to the warp factor of the metric the whole energy density suffers a depletion as it moves through the throat of the AdS space. This is the same phenomena that was used to explain the hierarchy problem in the original Randall-Sundrum papers [12]. As one moves away from the brane, the mass scales shrink down; what is a large scale on the brane at $z = 0$ looks exponentially small at any other point on the fifth dimension. This behavior helps to understand why the large energy deposited into the bulk by the inflaton should appear small once the decay products are hidden behind the black hole horizon. Therefore, although we have not estimated the magnitude of the black

hole dark energy, we believe it should be harmless.

There are some alternatives to the picture presented here. For example, one could use a bulk field to provide for the inflaton as its quasi-localized (resonant) mode as described at the end of previous section. It is interesting to note that the width of such a mode, given by Eq. (2.15), has the same functional form as Eq. (3.4), so that its escape rate from the brane would be as efficient as the decay of the inflaton in the our present model.

IV. A STRINGY MOTIVATION

In string theories inflationary cosmologies have often been discussed (see. e.g. [15]) by making use of the fact that Dp and $\bar{D}p$ branes can attract each other by virtue of the spacetime supersymmetry breaking [30]. If the attractive potential is sufficiently flat then it can give rise to a slow roll inflation [31]. One of the constraints is that the brane separation and hence the bulk has to be larger than the inverse of the compactification scale, which is indeed a problem [32] and can be viewed as an initial condition problem requiring some kind of a bulk inflation [33] before brane inflation. Such early inflation could be triggered, e.g. by gas of branes [34].

An important issue is the stabilization of the volume, the dilaton and the moduli. In the context of a warped background one typically finds a Klebanov-Strassler kind of solution for the background metric [35]. One can think of this geometry as a stringy generalization of the Randall-Sundrum model, where there is an adS throat (or a conical singular region) where the infrared brane can be regularized by the infrared geometry. The Klebanov-Strassler solution gives rise to a non-compact geometry where the radial internal coordinate can be thought of as z in the 5 dimensional language of Randall-Sundrum warped geometry. The Planck brane is at the large r ultraviolet region, while the small r infrared brane is stuck near the adS throat with, where r parameterizes the internal radial coordinate and the metric is of the form

$$ds^2 = h^{-1/2}(r) dx_\mu dx^\mu + h^{1/2}(r)(dr^2 + r^2 ds_{(5)}) \,. \tag{4.1}$$

A particular realization of such compactification on a Calabi-Yau manifold gives rise to the stabilization of the complex structure moduli [36, 37, 38].

In this paper we will not be able to discuss a detailed inflationary model within such stringy framework. We will merely present some plausibility arguments supporting our case

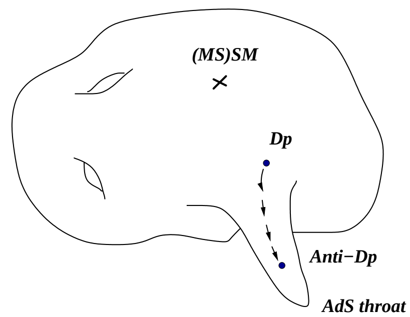

FIG. 1: An illustration of a manifold which has singular points with non-trivial fluxes, and which yields the adS geometry. The cross denotes the point in moduli space where MSSM branes are fixed, while there is a $\bar{D}3$ situated close to the warped geometry near adS throat, and the $D3$ brane is attracted towards the $\bar{D}3$ brane, thereby giving rise to inflation along three spatial directions, which we assume to be parallel to MSSM branes. Reheating occurs near the adS throat. The excited modes from reheating are trapped near the throat.

as discussed in Sect. III . To this end, let us consider a scenario which consists of a stack of branes mimicking MSSM gauge group (stack of $D3$ branes and $D7-\bar{D}7$ branes (the latter ones required for an exact cancellation of the tadpoles at the singularity). In addition, there should be other branes and anti-branes to drive inflation along the three spatial directions. The MSSM branes are embedded near the ultraviolet part of the geometry, at large r, far from the adS throat, while the branes which give rise to inflation are moving towards the region where the adS throat is located, near the infrared part of the geometry, at small r.

To be concrete, let us assume that all the moduli are stabilized like in [38]. A set of $\bar{D}3$ branes are stuck near the infrared part of the bulk, and inflation occurs because of the slow motion of a $D3$ brane approaching from the ultraviolet regime. The potential of $D3-\bar{D}3$ is also felt by the MSSM branes and is described by a four dimensional effective field theory on the world volume. The presence of $\bar{D}3$ branes break supersymmetry and give rise to a metastable positive vacuum energy state, which is also being felt along the three spatial dimensions. This acts as a source for inflation [38, 39] on the MSSM branes. We have depicted this framework in Fig. 1.

We assume that enough inflation can be obtained along the three spatial dimensions of the MSSM branes. In the brane anti-brane scenario inflation ends when the separation becomes close to the string scale, whence the open string tachyon on the world volume

condenses [16], resulting in an annihilation of the pair of branes. Similar situation could arise in our case. The rolling tachyon couples to the gauge fields living on the brane through covariant derivatives. The annihilation of branes ultimately gives rise to a long excited closed string along the inflated directions [40]. The long closed string decays very late into lighter closed string modes. However, the important point to note here is that only the bulk degrees of freedom near the adS throat are excited. This is so because the branching ratio of the closed string decaying into the bulk is still greater compared to decay into brane degrees of freedom by virtue of phase space arguments. These modes are actually trapped near the infrared regime which is energetically more favorable due to low energy configuration.

This situation is indeed quite similar to the 5 dimensional adS Randall-Sundrum model described in Sect. III. There the bulk quanta were dumped towards the adS horizon to form a black hole. Formation of a long closed string after the end of inflation also has a counterpart in field theory. If the inflaton has a global $U(1)$ charge, it may not decay completely but rather fragments into lumps known as Q-balls [41].

The main point here is that the MSSM branes are not directly reheated from the decay of the long closed string. They will certainly feel the resulting effective dark energy, but due to the warped metric the dark energy is redshifted.

V. DISCUSSION

During inflation, massless MSSM fields, or the (almost) flat directions corresponding to certain combinations of squarks, sleptons and Higgses, will be subject to fluctuations and form condensates. Like the ordinary inflaton, the condensates will receive scale-invariant spatial perturbations. Once the inflaton energy has disappeared into the bulk, the potential terms along some flat direction will eventually start to dominate the energy density of the MSSM brane. A potential arises because of non-renormalizable interactions and the soft supersymmetry breaking mass terms (for a review, see [3]). (In the cosmological context the Higgs coupling $\mu H_u H_d$ does not spoil flatness as μ is much smaller than the relevant field amplitudes).

Once the condensate decays, it will reheat the universe with MSSM degrees of freedom and imprint on the MSSM gas the inflationary perturbations. The flat direction condensate acts as an MSSM curvaton [8, 9, 10]. The simplest possibility is the flat direction that consists of

the Higgses H_u and H_d, which has been discussed in detail in [6]. The reheat temperature can be estimated to be less than 10^9 GeV. The amplitude of the fluctuations along the $H_u H_d$ direction can match the observed density perturbations in the CMB radiation and the spectrum with a spectral tilt very close to 1, with some weak dependence on the Higgs potential [6].

We have argued that a brane cosmology with a warped, infinite extra dimension allows for the inflaton to decay into the bulk and for the subsequent redshifting of the decay products. The inflaton decays efficiently into a continuum of Kaluza Klein modes which carry non-zero momentum along the extra dimension and move away from our four dimensional world, taking inflaton energy with them. In effect, the effective dark energy present on the MSSM brane will disappear into the bulk and be hidden behind the particle horizon at the infinity of the 5th dimension.

Although we have sketched a possible inflationary scenario involving $\bar{D}3$ and $D3$ branes that annihilate at an adS throat, a string theoretical model for reheating remains a challenge. Nevertheless, it seems that at least within brane world cosmologies it is possible to have the inflaton decay products disappearing into the bulk so that all matter could have its origin in the decay of the MSSM condensate rather than in the inflaton energy density.

VI. ACKNOWLEDGEMENTS

K.E. is supported partly by the Academy of Finland grant no. 75065, and A.M. is a CITA-National fellow and his work is also supported in part by NSERC (Canada) and by the Fonds de Recherche sur la Nature et les Technologies du Québec.

[1] C. L. Bennett. *et.al.*, "First Year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Preliminary Maps and Basic Results," Astrophys. J. Suppl. **148**, 1 (2003) [arXiv:astro-ph/0302207].

[2] D. H. Lyth and A. Riotto, "Particle physics models of inflation and the cosmological density Phys. Rept. **314**, 1 (1999) [arXiv:hep-ph/9807278].

[3] K. Enqvist and A. Mazumdar, "Cosmological consequences of MSSM flat directions," Phys. Rept. **380**, 99 (2003) [arXiv:hep-ph/0209244].

[4] K. Enqvist, S. Kasuya and A. Mazumdar, "Adiabatic density perturbations and matter generation from the MSSM," Phys. Rev. Lett. **90**, 091302 (2003) [arXiv:hep-ph/0211147].

[5] K. Enqvist, A. Jokinen, S. Kasuya and A. Mazumdar, "MSSM flat direction as a curvaton," Phys. Rev. D **68**, 103507 (2003) [arXiv:hep-ph/0303165].

[6] K. Enqvist, S. Kasuya and A. Mazumdar, "MSSM Higgses as the source of reheating and all matter," arXiv:hep-ph/0311224.

[7] M. Postma, "The curvaton scenario in supersymmetric theories," Phys. Rev. D **67**, 063518 (2003) [arXiv:hep-ph/0212005]. S. Kasuya, M. Kawasaki and F. Takahashi, "MSSM curvaton in the gauge-mediated SUSY breaking," Phys. Lett. B **578**, 259 (2004) [arXiv:hep-ph/0305134]. K. Hamaguchi, M. Kawasaki, T. Moroi and F. Takahashi, "Curvatons in supersymmetric models," arXiv:hep-ph/0308174.

[8] K. Enqvist and M. S. Sloth, "Adiabatic CMB perturbations in pre big bang string cosmology," Nucl. Phys. B **626**, 395 (2002) [arXiv:hep-ph/0109214].

[9] D. H. Lyth and D. Wands, "Generating the curvature perturbation without an inflaton," Phys. Lett. B **524**, 5 (2002) [arXiv:hep-ph/0110002].

[10] T. Moroi and T. Takahashi, "Effects of cosmological moduli fields on cosmic microwave background," Phys. Lett. B **522**, 215 (2001) [Erratum-ibid. B **539**, 303 (2002)] [arXiv:hep-ph/0110096].

[11] L. Randall and R. Sundrum, "An alternative to compactification," Phys. Rev. Lett. **83**, 4690 (1999) [arXiv:hep-th/9906064].

[12] L. Randall and R. Sundrum, "A large mass hierarchy from a small extra dimension," Phys. Rev. Lett. **83**, 3370 (1999) [arXiv:hep-ph/9905221].

[13] G. Aldazabal, L. E. Ibanez, F. Quevedo and A. M. Uranga, "D-branes at singularities: A bottom-up approach to the string embedding of the standard model," JHEP **0008**, 002 (2000) [arXiv:hep-th/0005067].

[14] F. Quevedo, "Phenomenological Aspects of D-Branes", Spring School on Superstrings and Related Matters, ICTP, Trieste (2002).

[15] F. Quevedo, "Lectures on string / brane cosmology," Class. Quant. Grav. **19**, 5721 (2002) [arXiv:hep-th/0210292].

[16] A. Sen, "Universality of the tachyon potential," JHEP **9912**, 027 (1999) [arXiv:hep-th/9911116].

[17] A. Mazumdar, S. Panda and A. Perez-Lorenzana, "Assisted inflation via tachyon condensation," Nucl. Phys. B **614**, 101 (2001) [arXiv:hep-ph/0107058].

[18] V. A. Rubakov, "Large and infinite extra dimensions: An introduction," Phys. Usp. **44**, 871 (2001) [Usp. Fiz. Nauk **171**, 913 (2001)] [arXiv:hep-ph/0104152].

[19] J. M. Maldacena, "The large N limit of superconformal field theories and supergravity," Adv. Theor. Math. Phys. **2**, 231 (1998) [Int. J. Theor. Phys. **38**, 1113 (1999)] [arXiv:hep-th/9711200].

[20] J.C. Long and J.C. Price, "Current short-range tests of the gravitational inverse square law," Comptes Rendus Physique **4**, 337 (2003) [arXiv:hep-ph/0303057]. J.C. long, *et al.*, Nature **421**, 922 (2003); "Upper Limits To Submillimeter-Range Forces From Extra Space-Time Dimensions," Nature **421** (2003) 922. C. D. Hoyle *et al*, "Sub-millimeter tests of the gravitational inverse-square law: A search for 'large' extra dimensions," Phys. Rev. Lett. **86**, 1418 (2001) [arXiv:hep-ph/0011014].

[21] W.D. Goldberger, M.B. Wise, "Bulk fields in the Randall-Sundrum compactification scenario," Phys. Rev. D **60**, 107505 (1999) [arXiv:hep-ph/9907218].

[22] S.L. Dubovsky, V.A. Rubakov and P.G. Tinyakov, "Brane world: Disappearing massive matter," Phys. Rev. D **62**, 105011 (2000) [arXiv:hep-th/0006046].

[23] A. Mazumdar and A. Perez-Lorenzana, "Sneutrino bangs," arXiv:hep-ph/0311106.

[24] P. Binetruy, C. Deffayet, D. Langlois, "Non-conventional cosmology from a brane-universe," Nucl. Phys. B **565**, 269 (2000) [arXiv:hep-th/9905012]. J.M. Cline, C. Grojean, G. Servant, "Cosmological expansion in the presence of extra dimensions," Phys. Rev. Lett. **83**, 4245 (1999) [arXiv:hep-ph/9906523].

[25] See also R.N. Mohapatra, A. Pérez-Lorenzana, C.A. de S. Pires, "Cosmology of brane-bulk models in five dimensions," Int. J. Mod. Phys. A **16**, 1431 (2001) [arXiv:hep-ph/0003328].

[26] A. Mazumdar, "Interesting consequences of brane cosmology," Phys. Rev. D **64**, 027304 (2001) [arXiv:hep-ph/0007269]. A. Mazumdar, "Post-inflationary brane cosmology," Nucl. Phys. B **597**, 561 (2001) [arXiv:hep-ph/0008087].

[27] R. Allahverdi, A. Mazumdar and A. Perez-Lorenzana, "Final reheating temperature on a single brane," Phys. Lett. B **516**, 431 (2001) [arXiv:hep-ph/0105125].

[28] A. Hebecker and J. March-Russell, "Randall-Sundrum II cosmology, AdS/CFT, and the bulk black hole," Nucl. Phys. B **608**, 375 (2001) [arXiv:hep-ph/0103214].

[29] C. Barceló, M. Visser, "Living on the edge: Cosmology on the boundary of anti-de Sitter space," Phys. Lett. B **482**, 183 (2000) [arXiv:hep-th/0004056].

[30] J. Polchinski, *String Theory* vol 1, 2, Cambridge University press, 1998.

[31] C. P. Burgess, M. Majumdar, D. Nolte, F. Quevedo, G. Rajesh and R. J. Zhang, JHEP **0107**, 047 (2001) [arXiv:hep-th/0105204]. J. Garcia-Bellido, R. Rabadan and F. Zamora, JHEP **0201**, 036 (2002) [arXiv:hep-th/0112147]. N. Jones, H. Stoica and S. H. Tye, "Brane interaction as the origin of inflation," JHEP **0207**, 051 (2002) [arXiv:hep-th/0203163]. K. Dasgupta, C. Herdeiro, S. Hirano and R. Kallosh, "D3/D7 inflationary model and M-theory," Phys. Rev. D **65**, 126002 (2002) [arXiv:hep-th/0203019].

[32] S. Kachru, R. Kallosh, A. Linde, J. Maldacena, L. McAllister and S. P. Trivedi, "Towards inflation in string theory," JCAP **0310**, 013 (2003) [arXiv:hep-th/0308055].

[33] A. Mazumdar, "Extra dimensions and inflation," Phys. Lett. B **469**, 55 (1999) [arXiv:hep-ph/9902381].

[34] R. Brandenberger, D. A. Easson and A. Mazumdar, "Inflation and brane gases," arXiv:hep-th/0307043.

[35] I. R. Klebanov and M. J. Strassler, "Supergravity and a confining gauge theory: Duality cascades and chiSB-resolution of naked singularities," JHEP **0008**, 052 (2000) [arXiv:hep-th/0007191].

[36] S. B. Giddings, S. Kachru and J. Polchinski, "Hierarchies from fluxes in string compactifications," Phys. Rev. D **66**, 106006 (2002) [arXiv:hep-th/0105097].

[37] A. R. Frey and J. Polchinski, "N = 3 warped compactifications," Phys. Rev. D **65**, 126009 (2002) [arXiv:hep-th/0201029].

[38] S. Kachru, R. Kallosh, A. Linde and S. P. Trivedi, "De Sitter vacua in string theory," Phys. Rev. D **68**, 046005 (2003) [arXiv:hep-th/0301240].

[39] A. R. Frey, M. Lippert and B. Williams, "The fall of stringy de Sitter," Phys. Rev. D **68**, 046008 (2003) [arXiv:hep-th/0305018].

[40] N. Lambert, H. Liu and J. Maldacena, "Closed strings from decaying D-branes," arXiv:hep-th/0303139.

[41] K. Enqvist, S. Kasuya and A. Mazumdar, "Reheating as a surface effect," Phys. Rev. Lett. **89**, 091301 (2002) [arXiv:hep-ph/0204270]. K. Enqvist, S. Kasuya and A. Mazumdar, "Inflatonic solitons in running mass inflation," Phys. Rev. D **66**, 043505 (2002) [arXiv:hep-ph/0206272].